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DEVELOPMENT OF FAILURE CRITERIA OF RIGID PAVEMENT THICKNESS REQUIREMENTS FOR MILITARY ROADS AND STREETS ELASTIC LAYERED METHOD

by

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The current design procedures of rigid pavements for military roads, streets, and open storage areas are reviewed. The two computer programs used in the current and the elastic layered method are described. The development of the procedure using elastic layered method and the discrepancies between the two procedures are presented.

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PREFACE

The work reported herein was funded by the US Army Corps of Engineers under the FIS-CS, Technical Support. Mr. Paige Johnson, US Army Corps of Engineers, was the Technical Monitor.

The study was conducted from January 1987 to July 1988 by the US Army Engineer Waterways Experiment Station (WES), Geotechnical Laboratory (GL), by Dr. Yu T. Chou, Pavement Systems Division (PSD). The work was under the general supervision of Dr. W. F. Marcuson III, Chief, GL, WES, and Mr. H. H. Ulery, Jr., Chief, PSD. This report was also written by Dr. Chou.

Acting Commander and Director of WES during the preparation of this report was LTC Jack R. Stephens, EN. Dr. Robert W. Whalin was Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic inch	27.6799	grams per cubic centimetre
square inches	6.4516	square centimetres
tons (2,000 pounds, mass)	907.1847	kilograms

DEVELOPMENT OF FAILURE CRITERIA OF RIGID PAVEMENT THICKNESS REQUIREMENTS FOR MILITARY ROADS AND STREETS ELASTIC LAYERED METHOD

PART I: INTRODUCTION

Background

1. The conventional procedure for the thickness design of rigid pavement for military roads and streets (Headquarters, Department of the Army and the Air Force, in preparation) is based on the stress calculations of Westergaard's solution (Westergaard 1925, 1926, 1939, 1948; Bradbury 1938). In recent years the elastic layered method (Burmister 1943, 1945; Mahta and Veletsos 1959; Michelow 1963; Peutz 1968; Koninklijke/Shell Laboratorium 1972) has been used in the Corps of Engineers (CE) for the design of both rigid and flexible airfield pavements (Brabston, Barker, and Harvey 1975; Barker and Brabston 1975; Parker et al. 1979) and for the design of both rigid and flexible pavements* for military roads, streets, and open storage areas.

Scope

2. This report contains the theoretical development of the Corps of Engineers design criteria for rigid pavements for military roads and streets. For convenience of discussion, the design procedure using the conventional method is reviewed, and the advantages of the elastic layered method to the conventional method is presented.

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* Headquarters, Department of the Army. "Pavement Design for Roads, Streets, and Open Storage Areas, Elastic Layered Method," Technical Manual, in preparation.

PART II: CONVENTIONAL DESIGN PROCEDURE

3. The design procedure for rigid pavement roads and streets based on the Westergaard solution is presented in TM 5-822-6/AFM 88-7, Chapter 1 (Headquarters, Department of the Army and the Air Force 1986). The background development of the procedure is given in Technical Report No. 4-18 (Ohio River Division Laboratories 1961). The procedure consists of two essential parts: (a) the design traffic is converted into equivalent 18,000-lb* single-axle, dual-wheel loading based on equivalent coverage factors and (b) the concrete slab stresses are computed using the Westergaard solution, and the thickness selected based on the design index (DI) which is a function of the traffic. These features are reviewed in the following paragraphs.

Equivalent Basic 18,000-lb Single-Axle, Dual-Wheel Loading

4. The loading used as a base for comparing all other vehicles was 18,000-lb on a single axle equipped with dual wheels. The wheel spacing selected was 13.5 by 58.5 by 13.5 in. The center to center spacing of the two sets of dual wheels was 72 in. Tire contact area was 54 sq in. per wheel.

Rigid Pavement Design Index

5. Figures 1 and 2 are coverages versus percent of design thickness for 5,000 coverages for military roads and streets. The curve was developed from full-scale accelerated traffic tests on airfield pavements for a traffic range from 40 to 30,000 coverages. For coverage levels beyond this range, the curve has been extended based on judgment plus a limited amount of data from laboratory research studies into the fatigue characteristics of concrete.

6. The entire range of vehicle types, loadings, and traffic intensities anticipated during the design life of pavements for the various classifications of military roads and streets were expressed in terms of an equivalent number of coverages of the basic loading. The overall range in the number of equivalent coverages of the 18,000-lb basic loading for the 25-year design life is from a minimum of 1 to a maximum of 182,500,000. To simplify the

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* A table of factors for converting non-SI units of measurement to SI (metric) is presented on page 3.

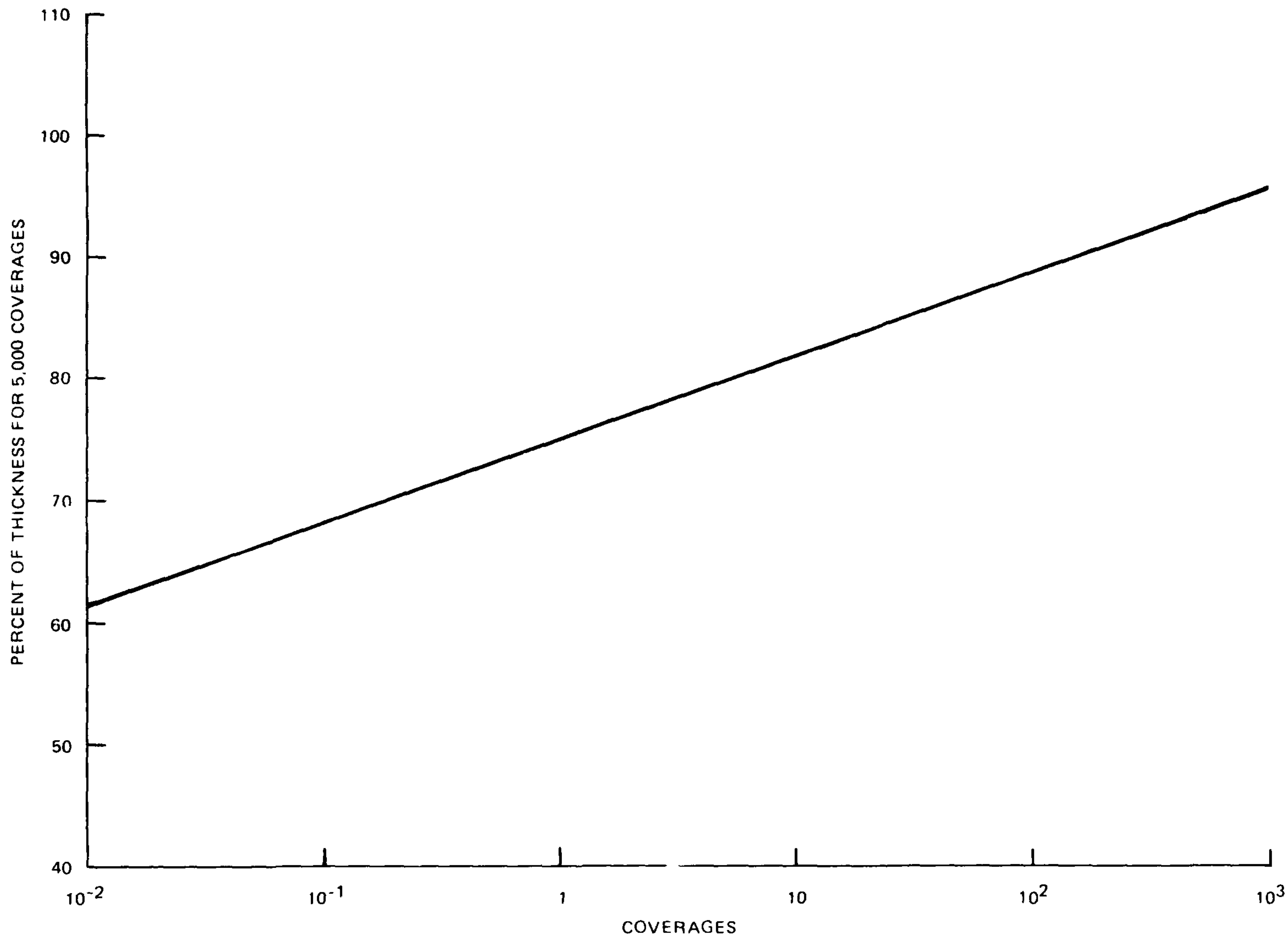

Figure 1. Coverages versus percent rigid pavement thickness for military roads and streets

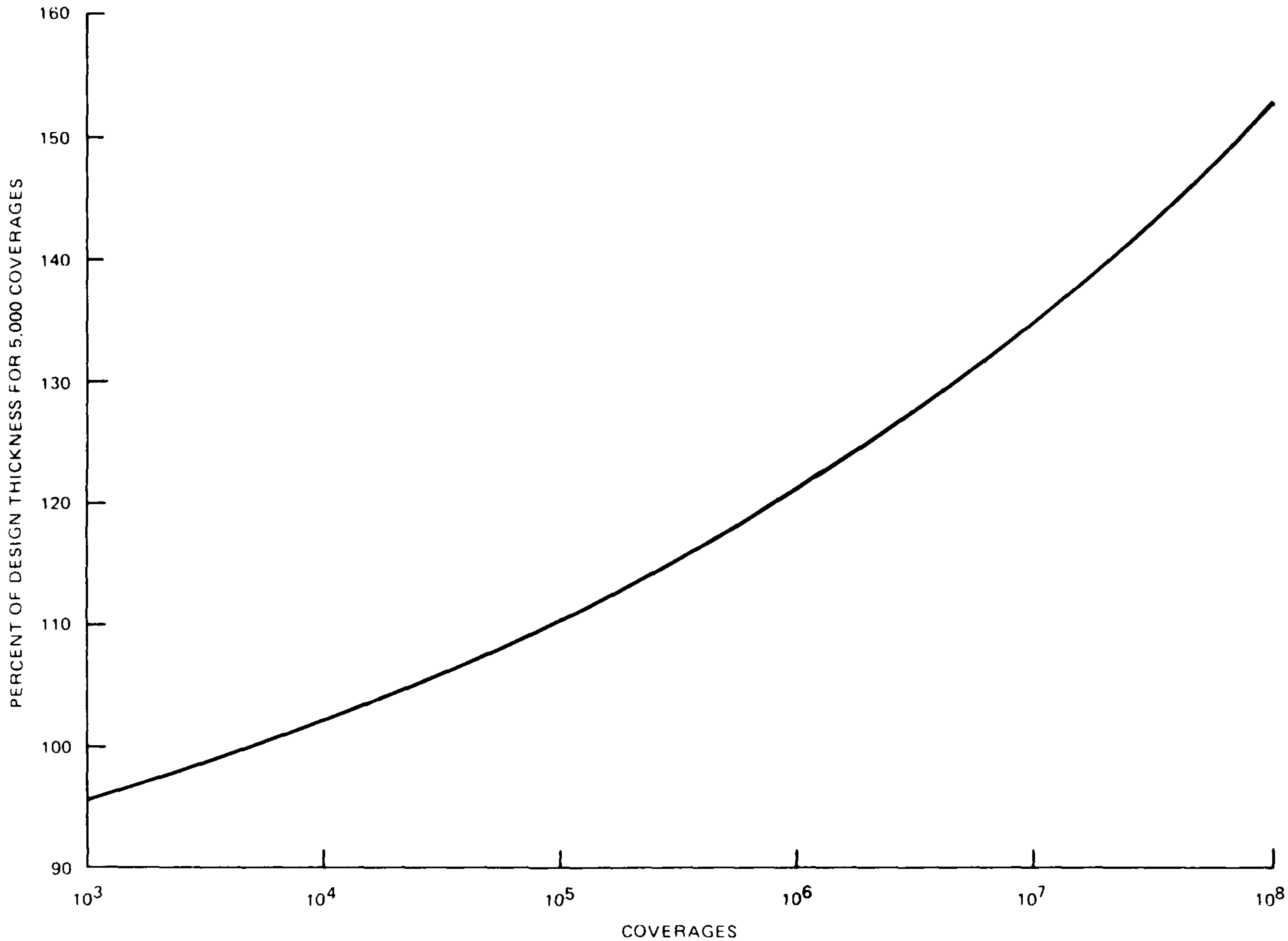

Figure 2. Coverages versus percent rigid pavement thickness for military roads and streets

design procedure, this range of equivalent coverages was expressed in terms of a numerical scale defined as the rigid pavement design index (DI). This index extends from 1 through 10 with an increase in the index number corresponding to an increase in the number of equivalent coverages of the basic loading.

7. In developing the scale for the DI, it was desired that each unit of the scale represent a uniform change in the required pavement thickness. To accomplish this, it was necessary to first interrelate the index scale with both equivalent coverages of the basic loading and the percent of pavement thickness required to sustain 5,000 coverages of this basic loading. Referring to Figures 1 and 2, the percent of the 5,000-coverage thickness required for 1 and 182,500,000 coverages is 75 percent and 159 percent, respectively. Using 11 coverages as a minimum and 180,000,000 coverages as a maximum, the percent of the 5,000-coverage thickness required is 82 percent and 158.5 percent, respectively. Dividing the difference between 82 and 158.5 into nine equal parts to provide an index from 1 to 10 resulted in a percentage change in thickness of 8.5 percent for each unit change in DI. This established the relationship between the percent of 5,000-coverage thickness and the DI. Corresponding values for the number of equivalent coverages of the basic loading were then determined from Figures 1 and 2.

8. Using a spread of plus or minus 4.25 percent from the median value of the percent of 5,000-coverage thickness, a range of values for the number of equivalent coverages of the basic loading was established for each unit on the DI scale. A summary of the percent of 5,000-coverage thickness and the number of equivalent coverages* of the basic loading are shown in Table 1 for each value of the rigid pavement DI.

Equivalent Coverage Factors

9. The relative loading equivalencies between the basic 18,000-lb axle loading and all other vehicle loadings were established through the development of "Equivalent Coverage Factors." The factors for various vehicle types are tabulated in Table 2. Essentially, these factors represent the equivalent number of coverages of the basic loading that is applied by a single operation

* It is noted that the pass-per-coverage ratio is the same for a single axle in flexible and rigid pavements; the ratio doubles for a tandem axle in the rigid pavement than in the flexible pavement.

Table 1

Relationship Between Rigid Pavement Design Index and Equivalent Coverages of the Basic Loading

Rigid Pavement Design Index*	Percent Thickness for 5,000 Coverages	Range of Equivalent Coverages Minimum	Range of Equivalent Coverages Maximum	Coverages of the 18,000-lb Basic Loading*
1	82.0	1	45	11
2	90.5	45	600	175
3	99.0	600	13,000	3,250
4	107.5	13,000	130,000	45,000
5	116.0	130,000	800,000	350,000
6	124.5	800,000	3,500,000	1,750,000
7	133.0	3,500,000	14,000,000	7,000,000
8	141.5	14,000,000	40,000,000	25,000,000
9	150.0	40,000,000	110,000,000	70,000,000
10	158.5	110,000,000	300,000,000	180,000,000

* Note that the relationships between the design index and the coverages of the 18,000-lb basic loadings are different for rigid and flexible pavements.

of the various representative configurations at their design loadings. The term "coverage" is defined as the number of maximum stress repetitions that occur at the critical location in the pavement as a result of the single operation of the particular vehicle load. The pass-per-coverage ratios, i.e., the number of passes (or operations) required to produce one coverage for various types of vehicle can be found in Technical Report No. 3-582 (US Army Engineer Waterways Experiment Station 1961). In the case of an 18,000-lb single-axle, dual-wheel loading, the pass-per-coverage ratio is 2.64. Thus, it takes statistically 2.64 passes of the load to produce one maximum stress at a certain critical location of the pavement. In a 12-ft-wide highway pavement lane, this critical location may be 0 to 3 ft away from the edge of the lane where the pavement experiences the most traffic.

10. The equivalent coverage factors in Table 2 were determined based on the fatigue criterion in Figures 1 and 2 and required thickness computation

Table 2

Equivalent Coverage Factors, Rigid Pavements

Vehicle Type	Design Loading (lb)	Maximum Loading (lb)	Vehicle Operations Per Coverage	Equivalent Coverage Factor
Passenger cars	3,900	4,500	4.79	1.4×10^{-10}
Panel & pickup trucks	5,500	6,000	4.63	1.6×10^{-9}
2-axle trucks & buses	15,000	26,000	2.10	1.45×10^{-4}
3-axle trucks	35,500	44,000	1.13	0.0288
4-axle trucks	50,200	58,000	0.841	0.0444
5-axle trucks	62,400	68,000	0.677	0.0290
Forklift trucks	5,500	6,000	7.28	1.70×10^{-4}
Forklift trucks	8,400	10,000	6.84	0.0400
Forklift trucks	12,000	15,000	6.32	4.25
Forklift trucks	16,000	20,000	5.28	31.0
Forklift trucks*	25,000	35,000	3.52	205
Track vehicles	15,000	20,000	1.43	1.82×10^{-4}
Track vehicles	33,000	40,000	0.750	0.0342
Track vehicles	55,000	60,000	0.432	1.66
Track vehicles	80,000	90,000	0.360	31.0
Track vehicles	105,000	120,000	0.334	195

* One operation of the 25,000-lb forklift truck is equivalent to 205 coverages of the basic 18,000-lb, single-axle, dual-wheel loading.

using the Westergaard solution (edge load condition) in accordance with Equation 1

$$h = \left[\frac{6P}{\sigma}\left(1.55 \quad \frac{M}{p}\right)\right]^{1/2} \tag{1}$$

where

P = wheel load, in lb

σ = 650 psi, the design stress in pavement

1.55 = sum of the impact factor* 1.25 and the load repetition factor 1.3 (for 5,000 coverages)

M/p = maximum moment per pound of wheel load induced by all wheels on the axle. M/p values can be determined in a chart (available in Figure 1 of Technical Report No. 4-18) from the values of A/ℓ^2 where A is the contact area of the wheel load and ℓ** is the radius of relative stiffness of the pavement. A single value for ℓ of 36.51 in. was selected for all computations which was determined for a pavement thickness of 8 in. and a subgrade k of 100 pci

The purpose of these (impact and load repetition) factors is to reduce the flexural strength of the concrete and thus to increase the pavement thickness.

11. The computations are carried out in the following steps:

<u>a</u>. The pavement thickness t_1 required to sustain 5,000 coverages of the design loading is first computed.

<u>b</u>. The pavement thickness t_{18} required for 5,000 coverages of the 18,000-lb single-axle, dual-wheel loading is computed, and the percentage thickness t_1/t_{18} is calculated.

<u>c</u>. From Figures 1 and 2, the equivalent number of coverages of the basic loading C_1 is determined for the percentage thickness T_1/t_{18} , i.e., for a pavement thickness t_1 (5,000 coverages for the design loading), it would sustain the basic loading for C_1 coverages.

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* The impact factor for rigid pavement of roads and streets is not used in the present design procedure. The impact factor was never used in airfield pavement design.

** The radius of relative stiffness of the pavement ℓ is a function of slab thickness h and other parameters. Because the high speed electronic computer was not available in late 1950's, iterational procedures, which are commonly used nowadays in computer programs, were not used to calculate ℓ for particular k and h values.

d. Dividing C_1 by 5,000, one coverage of the design loading is equivalent to $C_1/5,000$ coverages of the 18,000-lb loading.

e. Assuming the pass (operation)-per-coverage ratio for the design loading is a_1 and dividing a_1 into the value $(C_1/5,000)$, one operation of the design loading is thus equivalent to $(C_1/5,000)/a_1$ coverage of the basic loading.

12. The equivalent coverage factors shown in Table 2 are determined following the steps mentioned above. It is noted, however, that the computations are made for each axle of the particular vehicle, and the equivalent coverage factor for the particular vehicle is the summing of the factors computed for each axle of the vehicle configuration.

Design Equation

13. In Technical Report No. 4-18 (Ohio River Division Laboratories 1961), an impact factor of 1.25 and a coverage factor of 1.3 were used. The coverage factor was used to account for the reduction of design stresses for 5,000 coverages. Explained in another manner, the coverage factor (1.3) extends the design life from one coverage to 5,000 coverages. The impact factor is not used anymore in current design of rigid pavement for roads and streets, and the coverage factor of 1.3 is replaced by Equation 2*

$$DF = \frac{R}{\sigma_e} = 0.5 + 0.25 \log_{10}(\text{coverage}) \qquad k \leq 200 \text{ pci} \tag{2}$$

where

DF = the design factor

R = flexural strength of the concrete

σ_e = free edge stress

It is to be noted that for 5,000 coverages the design factor is 1.42. In using Equation 2, the computed free edge stress for pavements with good load transfer needs to be reduced 25 percent to determine the pavement performance. In formulating Equation 2, the computed free edge stress σ_e were reduced 25 percent.

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* R. S. Rollings, in preparation, "Rigid Airfield Design Criteria," Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

14. Condition surveys of active airfields and the performance of the accelerated traffic section revealed that slabs on a high-strength foundation continued to perform well after a single crack is formed in the concrete slab. To take advantage of this performance, slab thickness requirements were reduced as shown in Table 3 (Hutchinson 1966) to allow some cracking to develop.

Table 3

Reduction in Pavement Thickness for High-Strength Foundations

Subgrade Modulus, k psi/in.	Reduction in Thickness, %
200	0.0
300	4.6
400	10.6
500	19.2

15. For computation convenience, Equation 3 may be used to replace Equation 2 and Table 3.

$$DF = \frac{R}{\sigma_e} = 0.7 - 0.001\ k + 0.25\ \log_{10}(\text{coverage}) \qquad (3)$$

$$k = 500 \text{ pci for } k \geqq 500 \text{ pci}$$

$$k = 200 \text{ pci for } k \leqq 200 \text{ pci}$$

Equations 2 and 3 are applicable for pavements with good load transfer at the joints (such as 25 percent load transfer) and the stress σ is the free edge stress. Equation 3 can be graphically presented in Figure 3. Note that the top line is drawn from Equation 2.

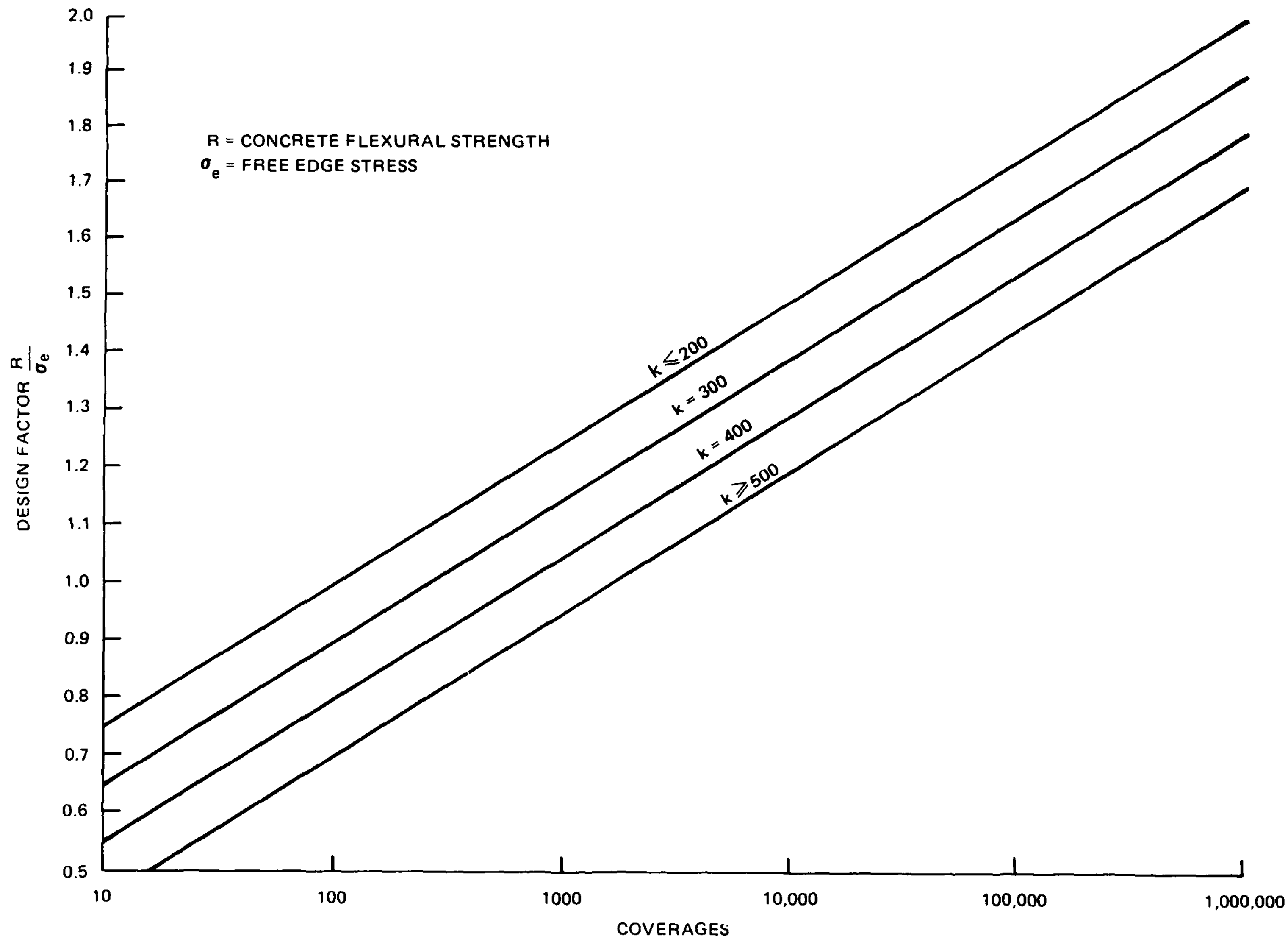

Figure 3. Fatigue relationships for concrete pavements, Westergaard solution

PART III: COMPUTER PROGRAMS, WESTERGAARD SOLUTION (H-51) AND ELASTIC LAYERED SYSTEM (BISAR)

16. The H-51 and BISAR computer programs have been used extensively at the WES for computing free edge stresses in rigid pavement and interior stresses at the center of rigid or flexible pavements, respectively. The free edge stresses are generally greater than the interior stresses. The theoretical background and its development of these two different methods are briefly explained below.

Westergaard's Solution (H-51)

17. The Westergaard's solution is derived based on the analogy of an elastic plate on dense-liquid foundation (Winkler Foundation). The theory was first formulated by E. Winkler in 1867 who assumed the intensity of the reaction of the foundation at any point was proportional to the deflection of the plate at that point. The settlement of the foundation at any point on its surface was assumed to be proportional to the pressure between the plate and the foundation at the same point, and consequently to be independent of the pressure elsewhere. This corresponds physically to the problem of a plate on a liquid base. It is also necessary to assume that the reactive pressures are vertical only; frictional forces are developed, but they are neglected.

18. Closed-form solutions were developed for stress conditions in a concrete slab resting on a dense-liquid foundation by Westergaard (1925, 1926, 1939, 1948) and for temperature-induced stresses by Westergaard (1926) and Bradbury (1938). Westergaard's formulas were then employed by Pickett and Ray (1951) for developing influence charts, which have been used by the Portland Cement Association (1955, 1966) for the design of highway and airport pavements. The H-51 computer program developed for Westergaard-type solutions (US Army Engineer Waterways Experiment Station 1967) is used at WES. In his original work, Westergaard considered three cases of loading: (a) corner load, (b) edge load, and (c) interior load. The H-51 program considers only the edge load condition as it is most serious in a concrete pavement.

19. The salient feature of the theory of plates is that it yields a two-dimensional solution. Because the plates are thin and the deflection is small, the assumption that the deformations at the surface and at the bottom

of the plate at a line normal to the plane of the plate are equal is qualified. Consequently, there is no variation of deformation in the direction of the thickness of the plate (linear variation of stress and strains), and the problem becomes two-dimensional.

20. In using the H-51 program, the elastic modulus in pounds per square inch and Poisson's ratio of the concrete and the subgrade modulus of reaction k in pounds per cubic inch are needed for input.

Elastic Layered System

21. The elastic solution for two- and three-layer systems was first developed by Burmister (1943, 1945) and later extended by Mehta and Veletsos (1959) to multi-layered systems. Although the method was developed for a three-dimensional problem, it is essentially two-dimensional because of the restriction of axial symmetry. For multiple-wheel problems, the method of superposition is used. The solution of the problem is based on the theory of elasticity. The material in each layer is assumed to be weightless, homogeneous, isotropic, and linearly elastic. The lowermost layer is considered to be of infinite extent in both the horizontal and the vertical directions. A continuous surface of contact between layers is assumed, and the interfaces are considered to be either rough or smooth. Across a rough interface there is no relative displacement in the horizontal direction, and the shearing stress is continuous. At a smooth interface, there is no shearing stress, and the radial displacements on either side of the common surface of contact are generally different.

22. Several computer programs have been developed based on the multilayer elastic theory to solve stress conditions in pavements. The most commonly used ones are CHEVRON (Michelow 1963) and BISAR (Koninklijke/Shell Laboratorium 1972). The former is limited to a single-wheel load and the latter can be used for multiple-wheel loads. The CHEVRON (Koninklijke/Shell Laboratorium 1972) program was later extended by Chou (1976) and Ahlborn (1972) to account for the effect of the nonlinear properties of pavement materials on pavement responses. The BISAR (Koninklijke/Shell Laboratorium 1972) program was also adopted by the US Army Corps of Engineers for the design of rigid pavements (Barker and Brabston 1975, Parker et al. 1979). BISAR program was used in this study.

23. The disadvantage of using the multilayer elastic theory for rigid pavement design is that the slab is assumed to be finite in the horizontal plane, and consequently, only the interior load case can be analyzed. Corner and edge stresses and joint conditions cannot be analyzed. For overlay design the BISAR program can assume the interface condition to be either smooth (unbonded) or rough (bonded); the program also has the capability of analyzing conditions that may be partially unbonded or bonded.

24. In using the BISAR computer program, the elastic moduli and Poisson's ratio of each layer of the pavement structure are needed for input. The applied loads to the pavement are considered as static, circular, and uniform over the contact areas. The following structural assumption is used in developing the failure criteria. The interface between the portland cement concrete (PCC) slab and the supporting subgrade is considered smooth with no bond, i.e., there is no frictional resistance at the interface.

PART IV: FAILURE CRITERIA, ELASTIC LAYERED METHOD

Background

25. Accelerated traffic tests were conducted to provide the basis for development and validation of the concrete design thickness and the relation between the traffic coverages and the design thickness (Ahlvin et al. 1971; Philippe 1944; Philippe and Mellinger 1952; Mellinger, Sale, and Wathen 1957). These traffic tests defined three failure levels: (a) initial failure when a slab contains a single crack, (b) shattered slab when cracking divides the slab into six pieces, and (c) complete failure when cracking divided the slab into approximately 35 pieces. Air Force requirements for performance with minimum maintenance established the failure criterion for design as an initial crack.

26. Pavement thickness requirements were expressed as a percent of standard thickness for varying subgrade k values as illustrated in Figure 4 (Ohio River Division Laboratories 1962). The 100 percent standard thickness is taken at 5,000 coverages. The reduction of percent thickness for higher k values is based on values shown in Table 3. Similar plots are available for shattered slab and complete failure conditions (Ohio River Division Laboratories 1962).

27. Recently, Rollings* reexamined the CE traffic test data and found that there were a number of test sections in which traffic was applied very close to the free edges and construction joints of the concrete slabs. Failures occurred in these areas earlier than areas where good load transfers were provided. Rollings concluded that lesser coverages than deserved in these test sections were recorded as a result of these unusually severe test conditions. When higher coverages were assigned to these test sections, Rollings found that the correlation between slab thicknesses and observed pavement performance were improved greatly. However, the correction was not incorporated in Equation 2. In Equation 2 the design factor (DF) defined to be the ratio of concrete flexural strength R to maximum edge stress σ was used instead of the percent thickness as presented in Figure 4. For subgrade modulus k higher than 200 psi, the percent reduction of pavement thickness

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* R. S. Rollings, "Rigid Airfield Design Criteria," in preparation, Technical Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

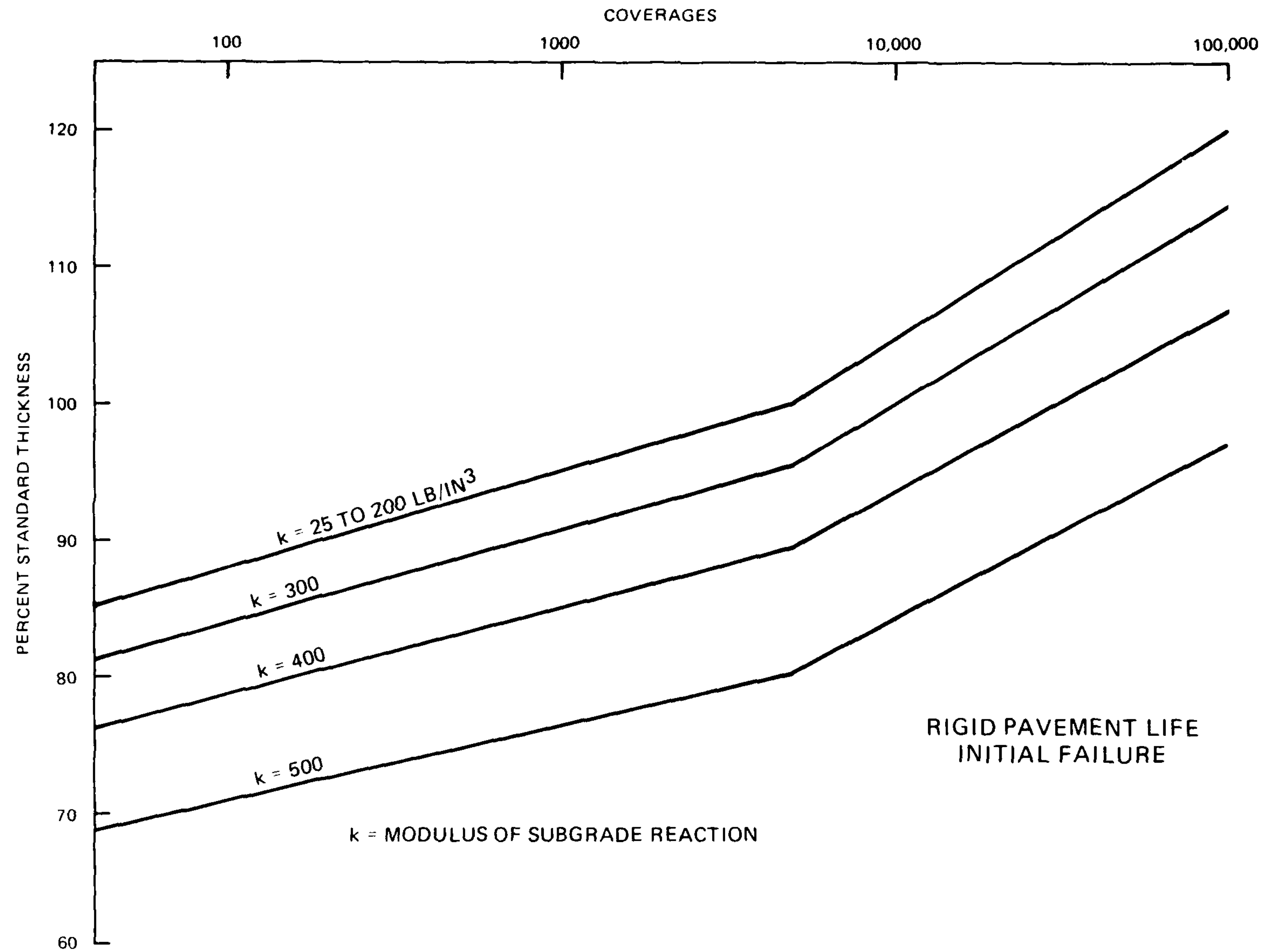

Figure 4. Pavement thickness requirement

is presented in Table 3. Dr. Walter Barker at WES incorporated the values in Table 3 for R > 200 pci to lines shown in Figure 4. Equation 2 and Table 3 form the basis of the structural design of concrete pavement for aircraft and vehicular loads based on Westergaard solution calculations.

Design Criteria

28. Parker et al. (1979) analyzed the CE full-scale accelerated traffic test data using the elastic layered method. The pavement information, calculated values, and failure coverages are tabulated in Table 4. The relationship between the DF and failure coverage plotted by Parker is presented in Figure 5.

29. The salient features of Figure 5 are:

   a. All the test sections had used doweled or keyed construction joints and contraction joints on short joint spacings that develop good aggregate interlock. Consequently, all of the relationships in the proposed design procedure are only valid for pavements that use these standard joints and develop typical levels of load transfer. It should be pointed out, however, that data points plotted in Figure 8 are very scattered. It is believed that discussions presented at the beginning of paragraph 29 explain partially the scattering.

   b. The stresses σ_{LT} are the maximum interior stresses computed using the BISAR computer program based on elastic layered method.

   c. Most test sections have subgrade modulus k values close to or less than 200.

   d. The DF is equal to R/σ_{LT}, where R is the flexural strength of the concrete measured from beam specimens cut from test concrete slabs.

   e. A straight line is drawn through the data points on a semilogrithmic scale. Although all the test sections were failed at coverage levels less than 10,000, it is justified to extend the relation into higher coverage levels; the justification is presented later in Part IV.

30. The best fit line shown in Figure 5 is plotted together with the line of Equation 2 and are compared in Figure 6. Note that the two criteria are developed based on the same test data but the computed stresses are by the Westergaard solution (edge stresses) in one criterion and by the elastic layered solution (interior stresses) in the other.

Table 4

Data for Development of Performance Criteria

Test Series	Test*	Type Load	Thickness in.	k, pci	R, psi	σ_{LT}, psi	Actual Coverages	Design Factor
Lockbourne No. 1	A-1	Dual-wheel	5.72	150	740	405	390.0**	1.54
	A-2	Dual-wheel	5.72	150	780	599	45.0	1.31
	B-1	Dual-wheel	5.50	75	740	504	187.0	1.47
	B-2	Dual-wheel	5.50	75	780	759	35.0	1.03
	C-1	Dual-wheel	5.50	70	740	558	200.0	1.33
	C-2	Dual-wheel	5.50	70	780	853	44.0	0.92
	D-1	Dual-wheel	5.50	75	740	572	450.0	1.30
	D-2	Dual-wheel	5.50	75	780	877	33.0	0.89
	E-1	Dual-wheel	5.75	104	740	505	430.0**	1.48
	E-2	Dual-wheel	5.75	104	780	771	77.0	1.02
	F-1	Dual-wheel	7.75	52	740	396	550.0**	1.87
	F-2	Dual-wheel	7.75	52	780	625	111.0	1.25
	K-3	Dual-wheel	9.44	90	735	570	72.0	1.29
	K-2	Dual-wheel	9.44	90	780	410	700.0	1.91
	N-2	Dual-wheel	8.00	75	780	564	150.0	1.39
	N-3	Dual-wheel	8.06	75	735	785	9.0	0.94
	O-2	Dual-wheel	9.46	75	780	458	573.0	1.70
	O-3	Dual-wheel	9.46	75	735	647	72.0	1.14
	P-2	Dual-wheel	7.58	95	780	632	262.0	1.24
	P-3	Dual-wheel	7.58	95	735	883	6.0	0.84

(Continued)

* Column headings:

k = the modulus of subgrade reaction

R = the modulus of rupture for the concrete slab

σ_{LT} = the interior stress as computed with elastic layered method

Actual coverage = actual coverage to failure or if a plus is used, it would mean section did not fail, and the coverage given is when traffic was terminated

Design factor = R/σ_{LT}

** Data point not used in analysis.

(Sheet 1 of 3)

Table 4 (Continued)

Test Series	Test	Type Load	Thickness in.	k, pci	R, psi	σ_{LT}, psi	Actual Coverages	Design Factor
Lockbourne No. 1	Q-2	Dual-wheel	9.44	109	780	465	1,390.0	1.68
(Continued)	Q-3	Dual-wheel	9.44	109	735	659	57.0	1.12
	U-2	Dual-wheel	5.83	207	780	527	88.0	1.51
	U-3	Dual-wheel	5.83	207	735	651	1.5	1.16
	A-REC	Dual-wheel	9.81	107	725	390	658.0	1.87
Lockbourne No. 2	E-1	Single-wheel	15.00	90	725	629	97.0	1.15
	E-2	Single-wheel	15.00	150	680	574	942.0	1.19
	E-3	Single-wheel	15.00	99	710	663	17.0	1.07
	E-4	Single-wheel	15.00	164	680	642	203.0	1.07
	E-5	Single-wheel	18.75	91	695	454	43.0	1.53
	E-6	Single-wheel	20.26	97	700	397	2,204.0†	1.72
	E-7	Dual-tandem	24.00	88	760	312	2,204.0†	2.44
	M-1	Dual-tandem	12.00	55	725	600	134.0	1.21
	M-2	Dual-wheel	15.00	55	725	446	2,204.0†	2.63
	M-3	Dual-wheel	20.00	55	725	295	2,204.0†	2.46
Lockbourne No. 3		Dual-wheel	6.00	62	800	976	18.0	0.82
Sharonville	57	Dual-wheel	20.00	27	740	315	34,650.0†	2.35
Channelized	58	Dual-wheel	18.00	30	740	373	34,650.0†	1.98
	59	Dual-wheel	16.00	47	730	394	7,600.0	1.86
	60	Dual-wheel	12.00	335	730	416	1,674.0	1.80
	61	Dual-wheel	14.00	300	730	349	3,867.0	2.43
	62	Dual-wheel	16.00	360	730	274	10,082.0	2.72
Sharonville	71	Dual-tandem	32.00	100	800	249	9,680.0†	3.28
Heavy	72	Dual-tandem	28.00	70	800	319	9,680.0	2.53
	73	Dual-tandem	24.00	70	800	401	2,115.0	2.00

(Continued)

† Data point not used in analysis.

(Sheet 2 of 3)

Table 4 (Concluded)

Test Series	Test	Type Load	Thickness in.	k, pci	R, psi	σ_{LT}, psi	Actual Coverages	Design Factor
MWHGL	1-C5	C-5A	10.00	60	725	580	221.0	1.25
	2-C5	C-5A	12.00	70	800	473	4,230.0	1.69
	3-C5	C-5A	14.00	74	700	394	1,400.0	1.78
	4-C5	C-5A	8.00	74	775	735	180.0	1.05
	2-DT	Dual-tandem	12.00	70	700	566	95.0	1.24
	3-DT	Dual-tandem	14.00	74	660	461	205.0	1.43
KLJS	1-C5	C-5A	8.00	250	905	656	54.0	1.39
	2-C5	C-5A	11.00	100	730	522	344.0	1.40
	3-C5	C-5A	10.00	80	810	580	22.0	1.40
	4-C5	C-5A	10.00	235	860	522	6,336.0	1.76
	4-DT	Dual-tandem	10.00	235	860	643	320.0	1.43
SSPS	3-200	Dual-tandem	15.00	120	900	463	3,215.0	2.00
	3-240	Dual-tandem	15.00	120	900	564	350.0	1.62
	4-200	Dual-tandem	15.00	150	870	463	4,660.0	2.00
	4-240	Dual-tandem	15.00	150	870	555	70.0	1.61

(Sheet 3 of 3)

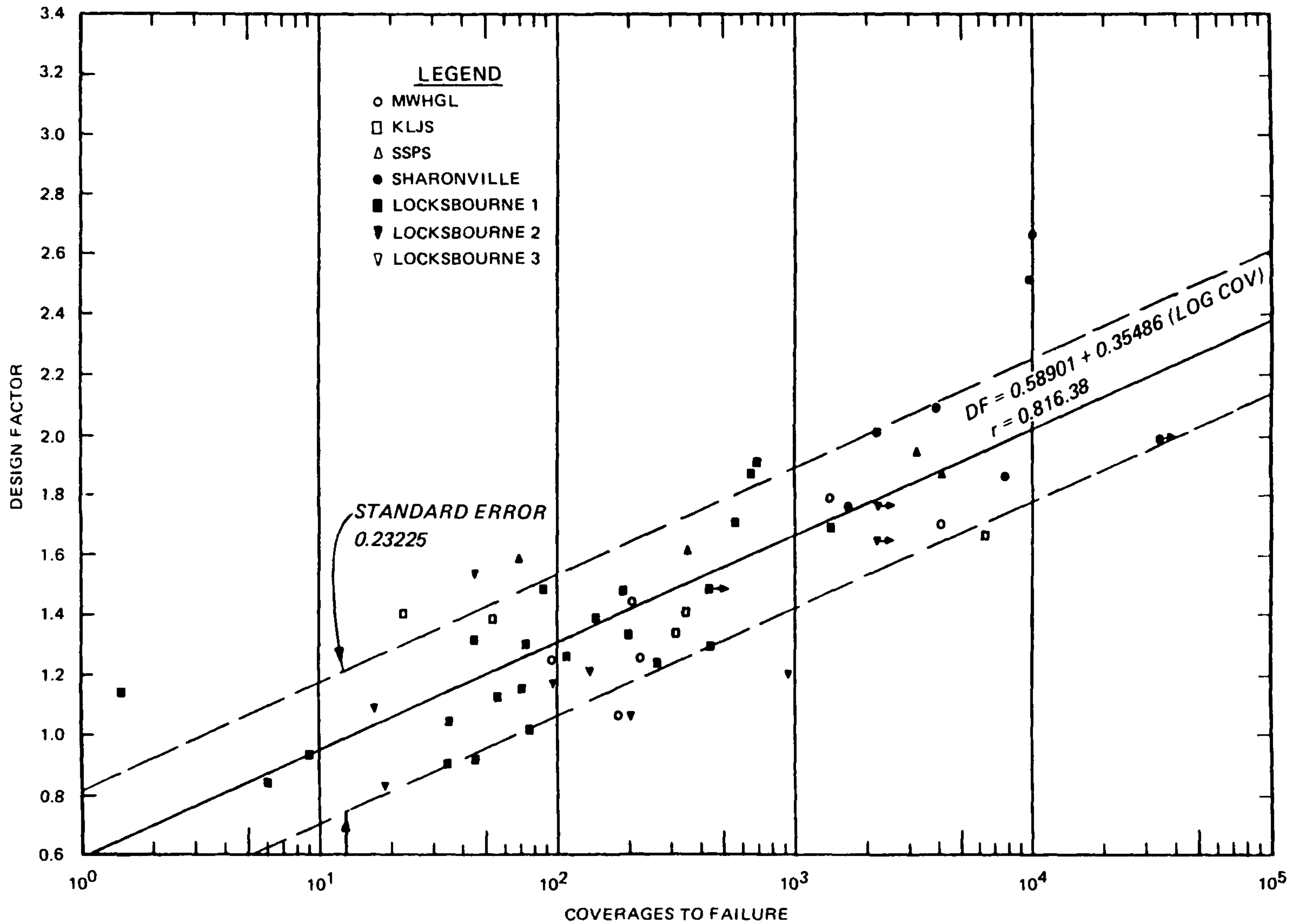

Figure 5. Performance criteria based on design factors listed in Table 4

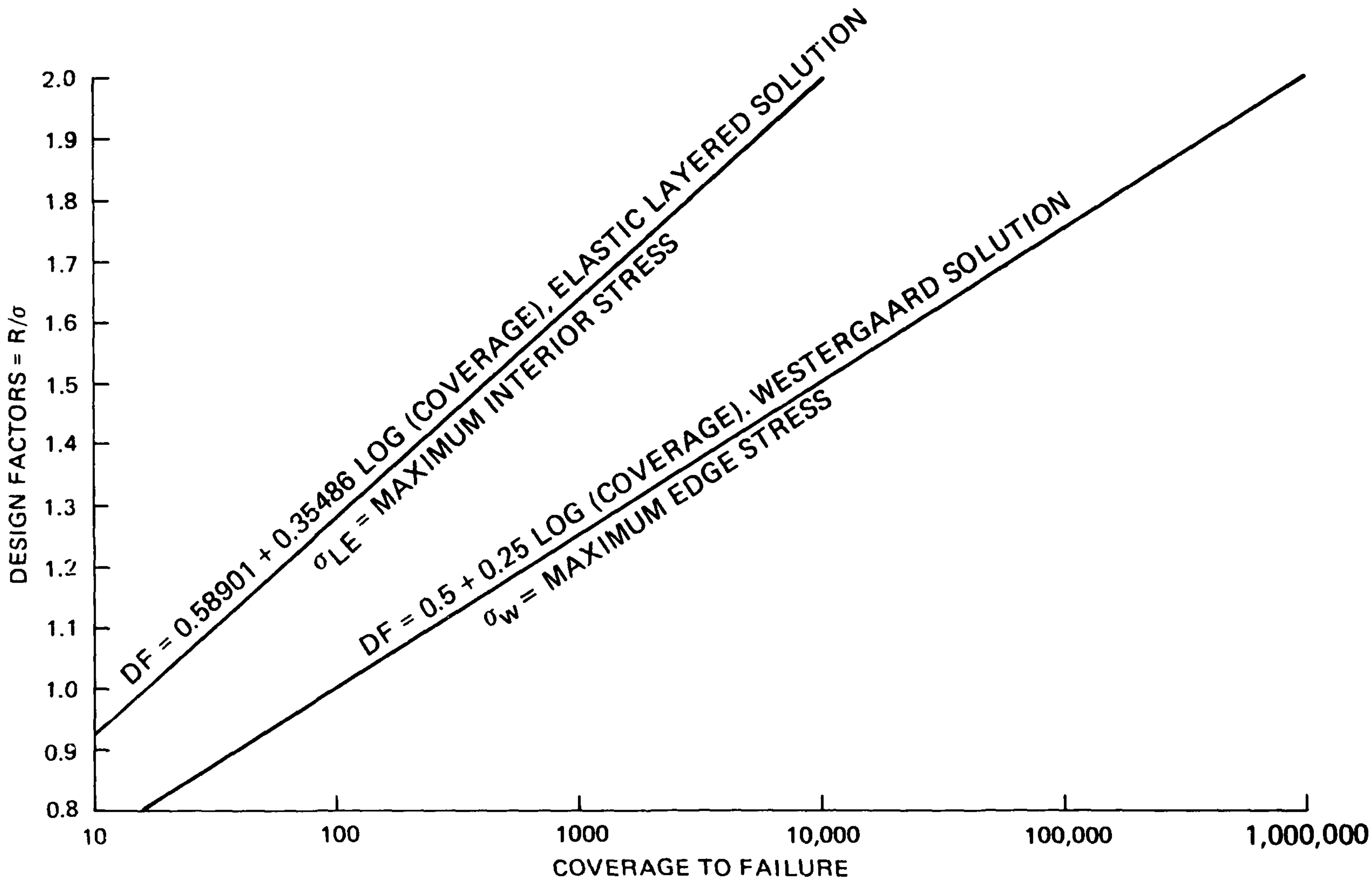

Figure 6. Comparison of failure criteria, Corps of Engineers test data

31. In the design of military roads and streets, tie bars are used between lanes, and dowel bars are used at contraction joints. Therefore, good load transfer is provided in the concrete slabs. However, since vehicular loadings travel very close to pavement edges, edge load conditions with no consideration of load transfer should be used in the design. Neither of the two criteria shown in Figure 6 is suitable for the design of military roads and streets using the elastic layered method because the lower line shown in the figure is strictly for the Westergaard solution and the upper line is developed using the elastic layered method for pavements with good load transfer. It is clear that the stresses computed using the elastic layered solution, i.e., interior stresses, are too conservative to simulate the actual free edge loading condition in roads and streets and can result in underdesign of the pavement due to unreasonably large design factor R . To remedy the situation, the layered elastic calculated stresses should be increased. The proposed method is determined based on two different approaches explained below.

Stress ratios

32. The ratios of the DF associated with elastic layered solution to the DF associated with Westergaard solution at various coverage levels in Figure 6 are tabulated in Table 5. Since $DF = R/\sigma$, the ratios are also the ratios of maximum edge stress σ_w to maximum interior stress σ_{LE} . Table 4 shows that for coverage levels ranging from 500 to 1,000,000, an average value of the ratio is about 1.33 which happens to be the reciprocal of 0.75, or $1.33 = 1/(1-0.25)$, where 0.25 happens to be the load transfer capability (25 percent) used by the CE for rigid pavements. It should not be construed however that for a given pavement, the maximum edge stress is always 1.33 times greater than the maximum interior stress. The two straight lines shown in Figure 9 are "statistically" the best-fit lines going through many test points, and the points plotted are rather scattered as shown in Figure 5. It is also important to realize that the maximum edge stress σ_w in Equation 2 was adjusted for the load transfer capability of the test pavements.

Rollings' procedure

33. Rollings (1987) developed a procedure for the design of rigid overlays for airfield pavements. The following information was cited by Rollings:

> The analytical model Rollings chose was the elastic layered method. To account for the effect of varying

degree of load transfer capability in the base slab, a multiplying factor X was proposed to adjust the layered elastic calculated interior stresses. To obtain more information on the relation between Westergaard edge and layered elastic interior stresses, both stresses were calculated for 60 hypothetical pavements. The aircraft loadings include F-4, B-707, B-723, B-747, and C-141 with modulus of subgrade reactions ranging from 50 to 400 pci and thickness ranging from 6 to 40 in. The stresses,* together with the stresses computed* by Parker et al. (1979), were plotted in Figure 7. Least square regression analysis was tried for the 120 data points, and a simple power relationship as shown below was developed.

$$\sigma_{LE} = 0.64\ \sigma_w^{0.972} \qquad (4)$$

where

σ_{LE} = stress from elastic layered analytical model

σ_w = stress from Westergaard edge loaded analytical model

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* The stresses are tabulated in Tables C.1 and C.2 of Rollings (1987).

Table 6

Design Factor Ratios and Stress Ratios (from Figure 6)

Coverage Level	(Design Factor, Elastic Layered) ÷ (Design Factor, Westergaard) = Stress σ_w ÷ Stress σ_{LE}
10	1.26
50	1.29
80	1.30
100	1.30
200	1.31
600	1.32
1,000	1.32
1,500	1.33
2,000	1.33
3,000	1.33
5,000	1.33
8,000	1.34
10,000	1.34
20,000	1.34
50,000	1.35
100,000	1.35
500,000	1.35
1,000,000	1.36

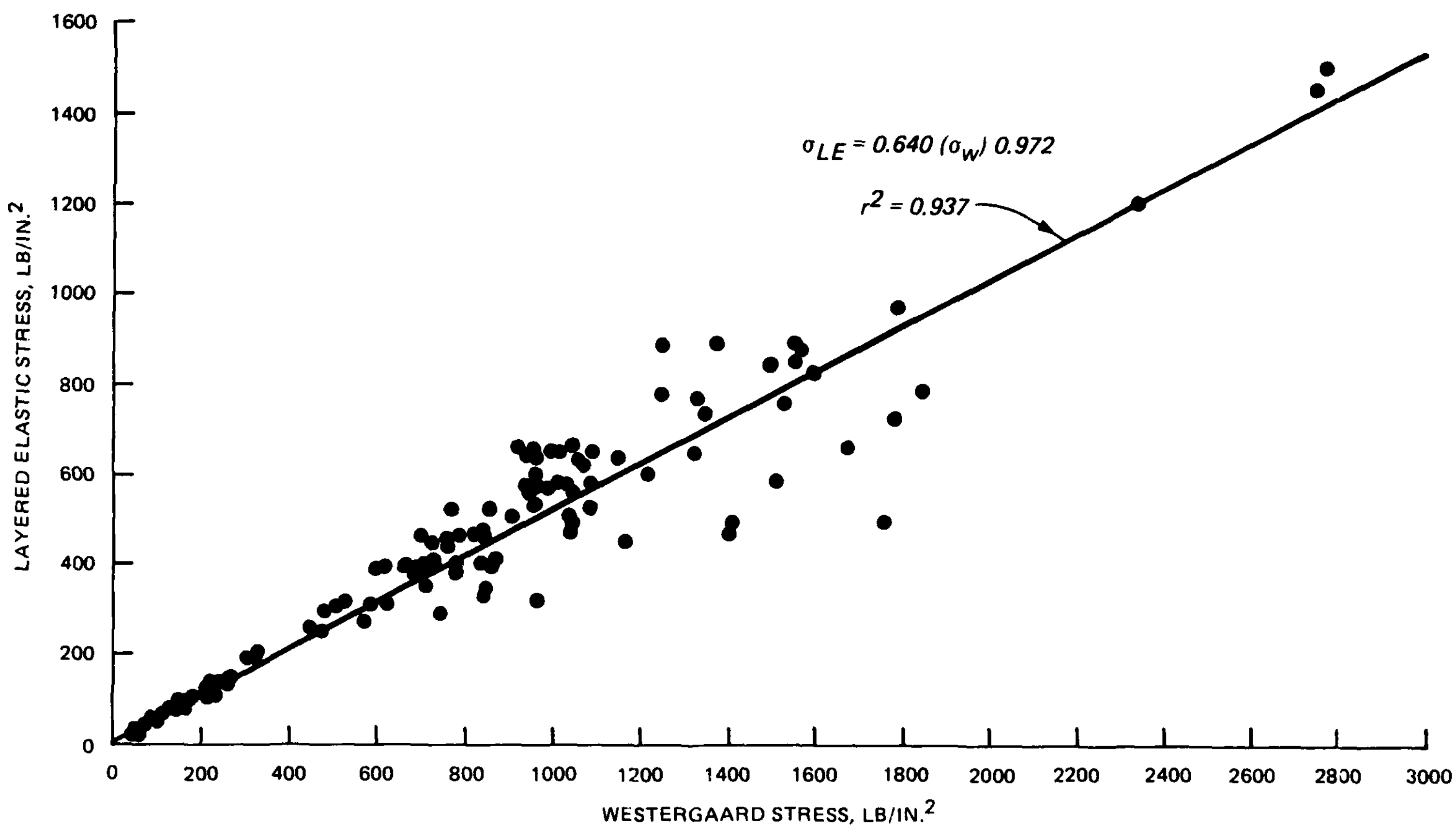

Figure 7. Relation between Westergaard and layered elastic calculated stresses, aircraft loadings (from Rollings 1987)

Equation 4 can be modified as

$$\gamma s_{LE} = 0.64(\beta\sigma_w)^{0.972} \tag{5}$$

where

γ = equivalent proportion of elastic layered stress to account for load transfer in the Westergaard stress

β = the proportion of the Westergaard stress used in design to account for load transfer, i.e., $1.0-\alpha$, where α is the load transfer to adjacent slab

It is apparent that γ is simply β raised to the 0.972 power. All the models and relationships developed for use were based on joints meeting the common 25 percent load transfer assumption. Normalizing the relation between γ and β for the standard 25 percent load transfer resulted in a multiplier, X , for the layered elastic stress as shown in Figure 8. The equation for the multiplier, X , is

$$X = \frac{(1-\alpha)^{0.972}}{0.7561} \tag{6}$$

This multiplier accounts for load transfer different from the standard 25 percent. If the load transfer meets or exceeds 25 percent, then no adjustment in stresses should be made. If the load transfer is lower than this value, the layered elastic calculated stresses in the base slab should be increased by multiplying them by the appropriate X from Figure 8. For instance, if the measured load transfer is 10 percent, the layered elastic calculated interior stresses in the concrete slab should be multiplied by 1.2.

34. It is important to note that at zero percent load transfer, the multiplier is 1.33 which is the value (1.33 = 1/0.75) derived previously for the ratio of the maximum edge stress to the maximum interior stress.

35. From the previous discussion, it seems to be reasonable to design rigid pavements using the elastic layered procedure with the following procedure for military roads and streets where load transfer is not considered.

a. Compute the maximum interior stress in the concrete slab using the elastic layered method (i.e., BISAR program), i.e., σ_{LE} .

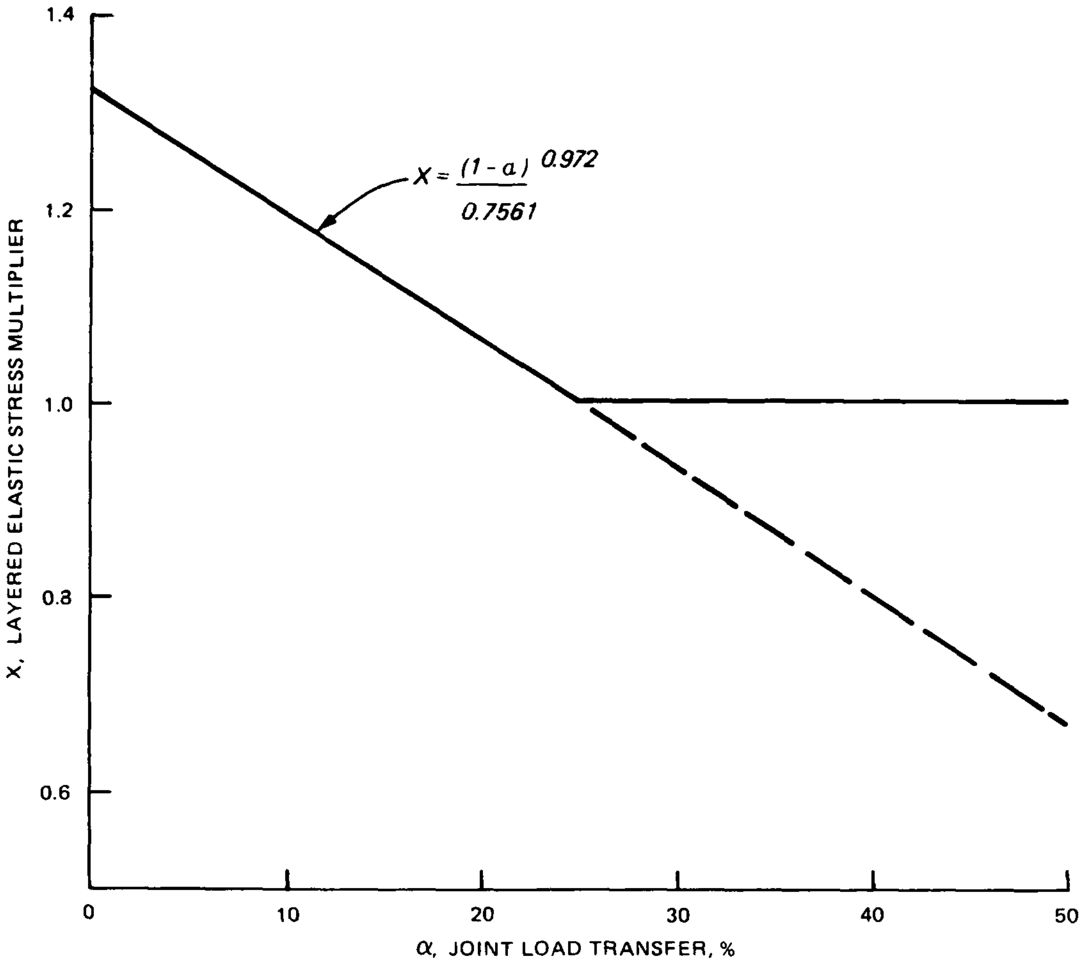

Figure 8. Multiplier for layered elastic stresses to account for load transfer (from Rollings 1987)

b. Multiply the layered elastic calculated stress with the factor 1.33 and determine the design factor DF = R/(1.33 σ_{LE}).

c. Determine the allowable coverage from the fatigue relationship

for k ≤ 200 pci DF = 0.58901 + 0.35486 LOG_{10} (coverage) (7)
(graphically shown in Figure 8)

for k > 200 pci use Table 3 and Equation 7

36. It is to be noted that the use of the multiplier 1.33 is not analytically proven. Continued research effort should be conducted to obtain a better solution. Ideally, the design criteria should be established based on results of full-scale field tests on pavements with wheel loads traveling close to the free edge of the concrete slabs.

37. Attempts were made to check if the relation between Westergaard and layered elastic stresses under aircraft loadings (Figure 7) also holds true

for vehicular loadings. More computations were made to obtain additional information for pavements under vehicular loadings. The pavement information, loads, and computed Westergaard and layered elastic stresses are tabulated in Table 6, and the relations are plotted in Figure 9. The solid line is the best-fit line for vehicular loadings drawn for Westergaard stresses up to 400 psi and the dotted line is the best-fit line for aircraft loadings from Figure 7. It is seen that for stresses in this range, which are generally the case in rigid pavements, the best-fit line for vehicular loadings is very close to that for aircraft loadings, indicating that the multiplying factor 1.33 derived from aircraft loadings can also be used for the design of rigid pavements for roads and streets. Note, however, that the difference between σ_{LE} determined by Equation 4 and the individual data points in Figure 9 is as much as 46 percent and that the scatter in Figure 9 is larger than that in the capable range in Figure 7.

Justification

38. Equation 7 is used for the design of rigid pavements for military roads and streets. However, two important features which are connected to the development of the failure criteria need to be explained.

Design factor DF less than and equal to 1

39. DF is the ratio of the flexural strength of the concrete R to the maximum stress σ induced by the load. For DF = 1 , the maximum stress is equal to the flexural strength of the concrete, i.e., the concrete slab will very likely experience its first crack during the first application of the load. However, the fatigue relationship at the top of Figure 6 shows that the allowable coverage is about 17 for a DF of 1. When the maximum interior stress is equal to the flexural strength of the concrete, the pavement can withstand 17 coverages* of the loading before the first crack is developed in the concrete slab. This is obviously an anomaly but there is not a rational

* In the case of edge loading, the fatigue relationship at the bottom of Figure 6 shows that when the maximum edge stress is equal to the flexural strength of the concrete, the pavement can actually withstand 100 coverages of the edge load before the first crack is developed in the concrete slab.

Table 6

Westergaard and Layered Elastic Stresses,* Vehicular Loadings

Type of loading, lb	No. of Wheels	Gear Dimension in.	h in.	Subgrade k psi	Subgrade E** psi	Stresses, psi Westergaard Solution σ_w	Stresses, psi Elastic Layered σ_{LE}	$\frac{\sigma_w}{\sigma_{LE}}$
18,000	4	13.5-58.5-13.5	10	50	4,100	261.2	140.0	1.87
Single-axle	4	13.5-58.5-13.5	6	50	4,100	559.6	294.0	1.90
Dual-wheels	4	13.5-58.5-13.5	10	400	59,000	182.4	77.1	2.37
	4	13.5-58.5-13.5	6	400	59,000	392.0	156.0	2.51
32,000	8	13.5-58.5-13.5	10	50	4,100	240.1	132.4	1.81
Dual-axle	8	48 center to center	6	50	4,100	443.2	244.4	1.81
Dual-wheels	8	48 center to center	10	400	59,000	138.8	59.4	2.34
	8	48 center to center	6	400	59,000	284.3	128.0	2.22
10,000	2	31 center to center	10	50	4,100	227.1	114.0	1.99
Forklift	2	31 center to center	6	50	4,100	567.7	268.0	2.12
	2	31 center to center	10	400	59,000	186.7	69.7	2.68
	2	31 center to center	6	400	59,000	418.3	160.0	2.61
15,000	2	35 center to center	10	50	4,100	340.2	167.0	2.04
Forklift	2	35 center to center	6	50	4,100	787.1	385.0	2.04
	2	35 center to center	10	400	59,000	263.3	101.0	2.61
	2	35 center to center	6	400	59,000	582.2	226.0	2.58
25,000	4	11-52-11	10	50	4,100	377.3	205.0	1.84
Forklift	4	11-52-11	6	50	4,100	809.7	430.0	1.88
	4	11-52-11	10	400	59,000	265.0	114.0	2.32
	4	11-52-11	6	400	59,000	550.3	226.0	2.43

(Continued)

* In the computation, the elastic modulus and Poisson's ratio of the concrete were 4,000,000 psi and 0.15, respectively. The Poisson's ratio of the subgrade soil was 0.4. The contact area was 54 sq in. per wheel. The layer between the concrete slab and the subgrade was assumed to be frictionless (AKL = 1,000 at BISAR).

** The elastic modulus of the subgrade soil was determined from the relation shown in Figure 10.

Table 6 (Concluded)

Type of loading, lb	No. of Wheels	Gear Dimension in.	h in.	Subgrade k psi	Subgrade E psi	Stresses, psi Westergaard Solution σ_w	Stresses, psi Elastic Layered σ_{LE}	$\frac{\sigma_w}{\sigma_{LE}}$
43,000	4	13-58-13	14	50	4,100	338.5	193.0	1.75
Forklift	4	13-58-13	10	50	4,100	557.2	320.0	1.74
	4	13-58-13	6	50	4,100	1,168.8	642.0	1.82
	4	13-58-13	14	400	59,000	235.5	108.0	2.18
	4	13-58-13	10	400	59,000	377.0	170.0	2.22
Tank	Tracks	See note+	6	400	59,000	766.0	314.0	2.44
60 tons			14	50	4,100	234.0	191.0	1.23
			10	50	4,100	354.9	287.0	1.24
			6	50	4,100	631.1	482.0	1.31
			14	400	59,000	131.7	81.8	1.61
			10	400	59,000	193.5	106.0	1.83
			6	400	59,000	325.6	140.0	2.33

+ The contact width and length of each track are 25 and 180 in., respectively. To simulate the uniformly distributed track load, nine circular loads having 25-in. diameter spaced 20-in. center to center were used; each load had a magnitude of 6,667 lb.

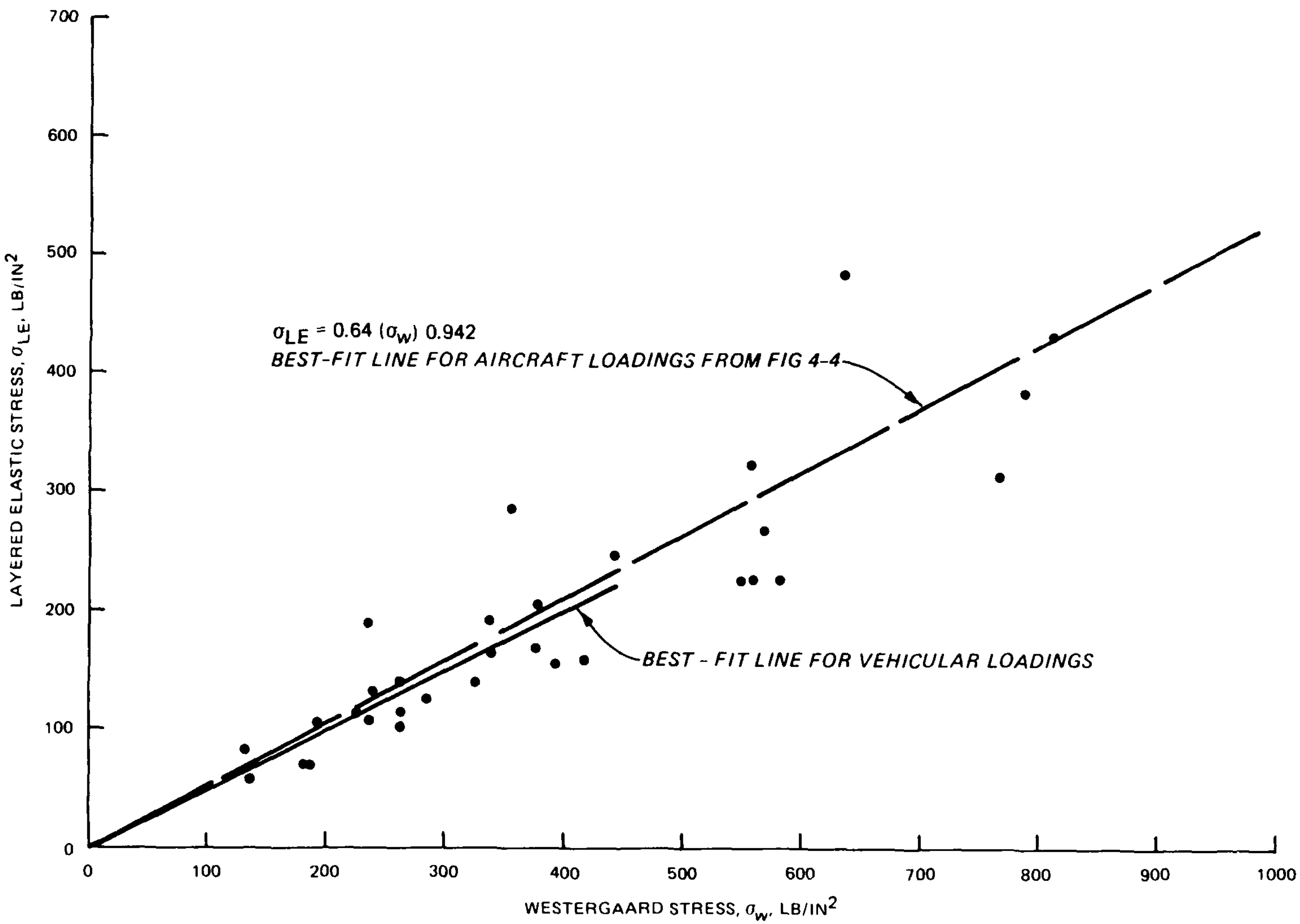

Figure 9. Relation between Westergaard and layered elastic calculated stresses, vehicular loadings

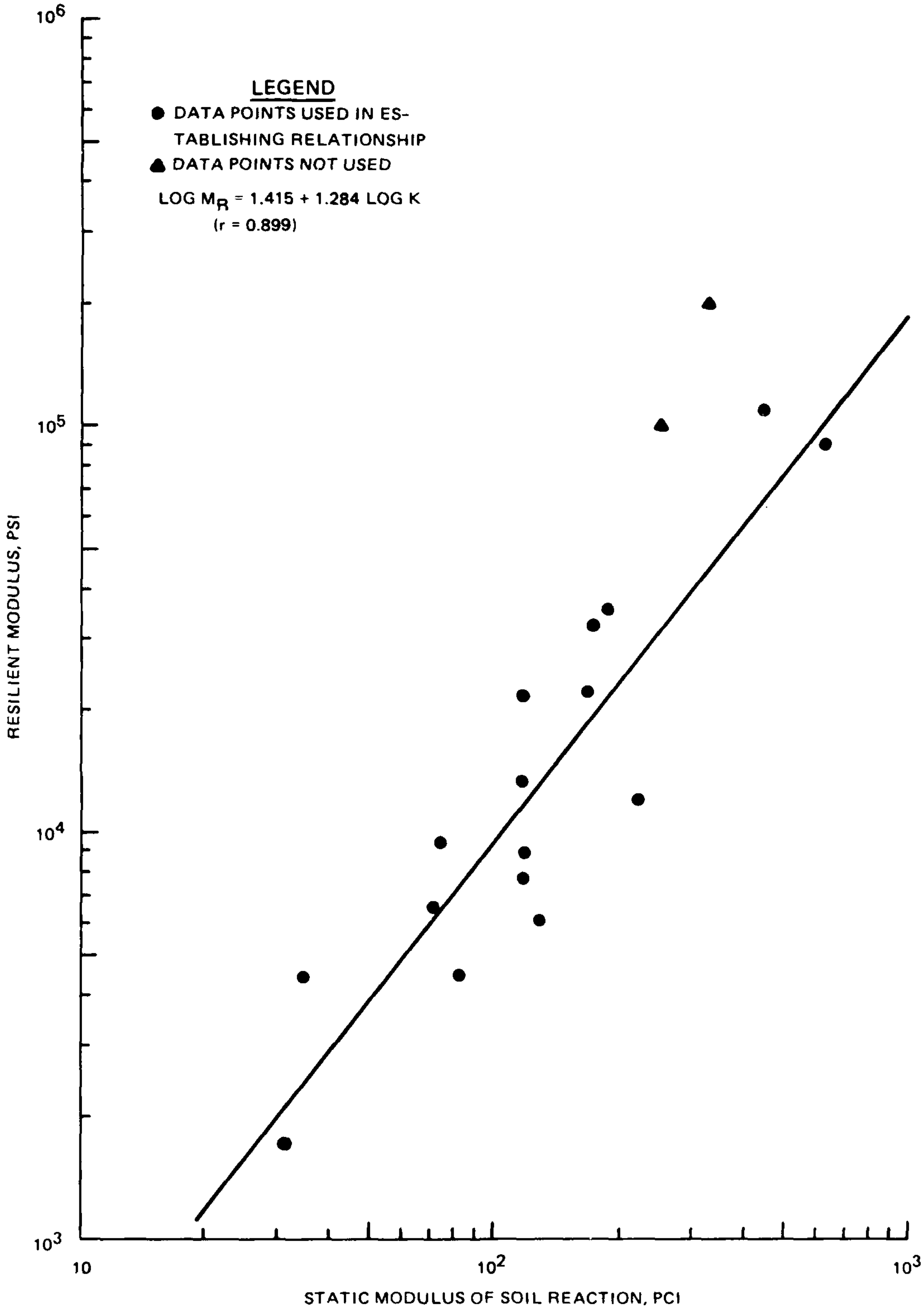

Figure 10. Correlation between resilient modulus of elasticity and static modulus of soil reaction (from Parker et al. 1979)

explanation available; the following clarification only provides some perceptions.

40. Equation 4 (or Equation 2) is determined as statistically the best-fit line plotted through numerous data points, which correlates the DF and coverage. Coverages are determined from full-scale accelerated traffic tests at the traffic level when the first structural crack at the surface of the concrete slab is "visually" observed. Flexural strength of the concrete R is determined from specimens cut from the pavement and tested in a simple-supported beam test. The maximum interior stress σ is a number computed using the BISAR program based on input elastic modulus E and Poisson's ratio ν of the concrete and the subgrade k modulus. However, the actual stresses in the slabs in the field are variable depending on the placement of the load, rate of loading, load transfer of joints, temperature, and moisture gradients. Consequently, the stresses calculated from the analytical models are nominal stresses reflecting the relative effect of imposed traffic loads rather than actual stresses. Also, it is likely that neither the laboratory determined flexural strength R represents the true flexural strength of the concrete nor the traffic level at which the initial structural crack becomes noticeable in the concrete slab surface is exactly the traffic level at which the initial crack really starts. The CE tests defined failure as occurring when one-half or more of the trafficking slabs have one or more structural cracks.

Straight line relation between design factor R and coverage level

41. Figure 11 is obtained from Rollings (1987) showing a comparison of several concrete fatigue relationships used or proposed for use in the design of concrete pavements. The following information was cited by Rollings:

> The Portland Cement Association (PCA) and the American Concrete Institute (ACI) relations are developed based on a conservative interpretation of laboratory cyclic beam tests at a low minimum to maximum stress ratio. The ACI (Rollings 1987) curves are for 5 and 50 percent probability of failure at a minimum to maximum stress ratio of 0.15. The developed curves are straight lines on a semilogarithmic plot. The other curves in Figure 11 are based on traffic tests and are different from these laboratory developed curves. The traffic tests provide information for the development of field fatigue relationships. The CE conducted large scale accelerated traffic tests using aircraft

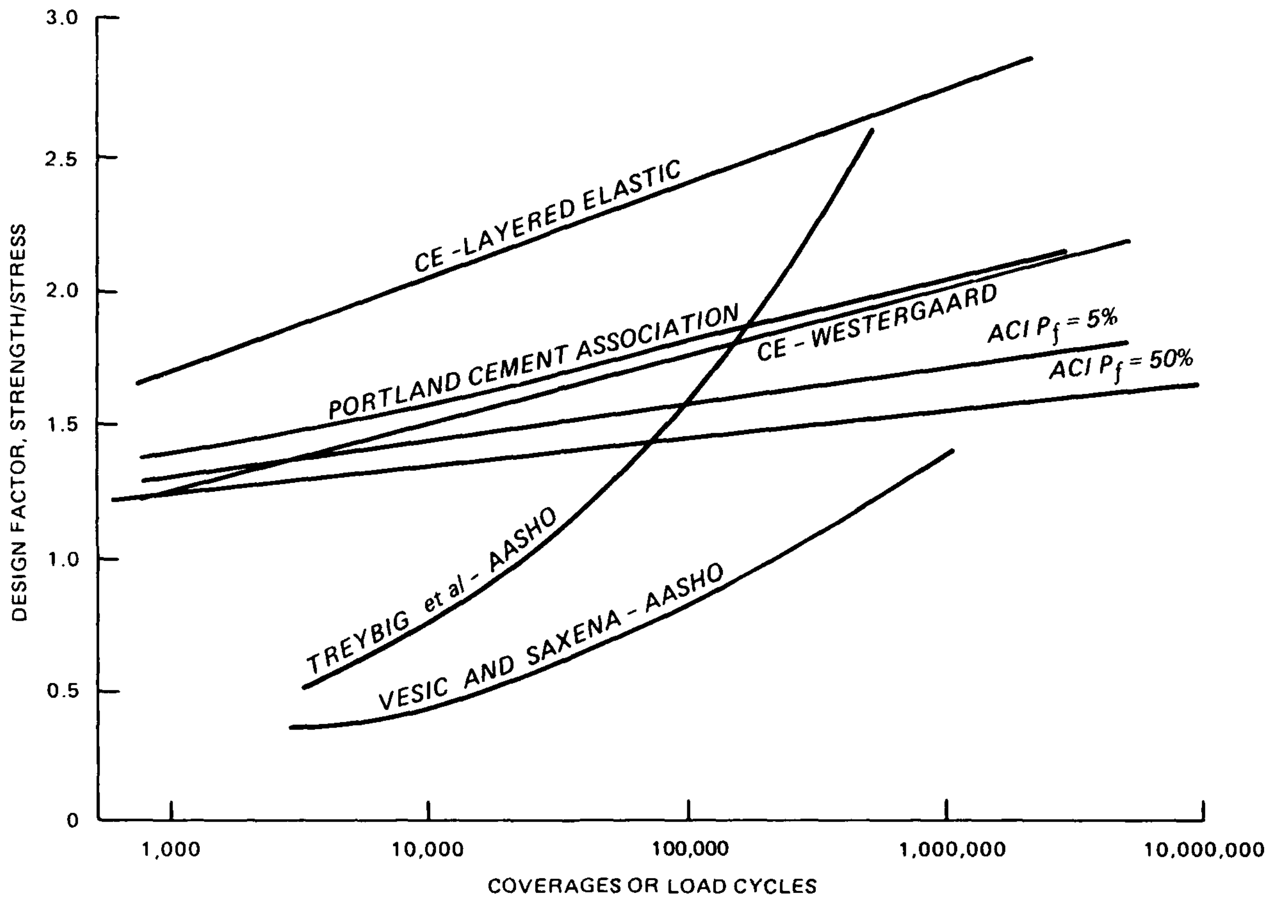

Figure 11. Fatigue curves for pavement design (from Rollings 1987)

size loads and gear assemblies, and the AASHO road test provided similar information for truck-sized axle loads. Both CE fatigue relationships are based on the same field tests, but one relation uses the elastic layered analytical model to calculate the stresses under the test load while the other uses the Westergaard edge load model. Each model calculates a different numerical value for the stress with the layered elastic calculated stress always being lower. Consequently, the resulting fatigue relation for each analytical model is different. The same effect is seen for the AASHO road test results in Figure 11 where Treybig et al. (1977) used the elastic layered model and Vesic and Saxena (1969) used the Westergaard edge load analytical model. The straight line presentations of CE curves are based on traffic tests failed at relatively low coverage levels. Question arises as to whether the straight line extension to very high coverage levels is justified.

Fatigue relationships based on field tests will vary depending on the analytical model used to calculate stresses and on the defined failure level.* The shape of relationships based on the AASHO roads is very different from other fatigue relationships. The ACI, PCA and both CE curves in Figure 11 are straight lines on a semilogarithmic plot whereas the AASHO relationships are sharply curved.

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* The CE tests defined failure as occurring when one-half or more of the trafficked slabs have one or more structural cracks. Vesic and Saxena (1969) defined failure as a pavement service index (PSI) of 2.5. As a comparison, the CE failure criteria would represent a PSI of 3.0 to 3.3. The relationship developed by Treybig et al. (1977) defined failure as the development of class 3 cracking in an AASHO road test section. A class 3 crack is a "crack opened or spalled at the surface to a width of 1/4 in. or more over a distance equal to at least one-half of the crack length" (Scrivner 1962).

42. Rollings (1987) pointed out that this difference is probably due to extensive pumping that developed at the AASHO road test. Consequently, AASHO road test relationships actually include the damage from both concrete fatigue and pumping. Pumping is a severe problem in highway pavements but less so in airfields. Rollings concluded that since the ACI and PCA curves are straight lines on a semilogarithmic plot based on laboratory tests and the tests cover

a wide range from low to very high load cycles, it is justified to extend the CE curves to high coverage levels in straight lines.

Comparison of Failure Criteria

43. An attempt was made to examine the differences among the various criteria presented in this report. Distress hypothetic pavements under the 18-kips single-axle dual-wheel load were examined. Stresses were computed using the H-51 and BISAR programs for each pavement which ranges in thickness and subgrade strength. Based on the computed stresses, coverages were determined from various failure criteria. The results are tabulated in Table 7.

44. Assuming good load transfer, coverages shown in Columns 6 and 7 are determined from layered elastic criteria (Figure 5) and Westergaard free edge computation (Equation 2). In the latter case, the stresses in the design factor were reduced 25 percent to account for good load transfer. Theoretically, coverage determined from both criteria should be quite close as both criteria were established based on the same field data. However, computed coverages shown in Columns 6 and 7 indicate that stresses computed from H-51 and BISAR programs can result in very different predicted coverages.

45. Assuming no load transfer coverages in Column 8 are determined from Equation 2 (Westergaard free edge solution) and the stresses are not reduced 25 percent. This is the condition for roads and streets in which load transfer is not considered. Coverages in Column 9 are determined from Equation 7, i.e., layered elastic procedure with the proposed modification in increasing the stress 1.33 times. Theoretically, the coverages in Columns 8 and 9 should be close. Wide scatter still exists in the predicted coverage values, as shown in the table, with lesser scatter in thicker pavements. However, the scatter seems to be lesser than that in the predicted values between Columns 6 and 7.

Table 7

Comparisons of Predicted Coverages

Concrete Thickness in. (1)	Subgrade E psi (2)	k pci (3)	σ_{LE} psi (4)	σ_w psi (5)	Layered Elastic with Load, Transfer (6)	Predicted Westergaard with Load Transfer (7)	Coverages Westergaard no Load Transfer (8)	Proposed Layered Elastic, no Load Transfer (9)
4	10,000	100	389	872	1,119	95	9.6	76
	7,000	80	424	905	457	68	7.5	39
	4,100	50	476	980	154	34	4.5	17
	2,000	30	549	073	47	17	2.6	7
6	10,000	100	229	478	2,182,172	178,830	2,750	22,606
	7,000	80	245	503	655,423	77,979	1,476	9,151
	4,100	50	271	545	125,670	22,953	590	2,643
	2,000	30	304	594	23,201	6,857	238	742
8	10,000	100	176	315	5.59 E+8	1 E+8	1,294,602	1,463,187
	7,000	80	185	327	1.74 E+8	4 E+8	893,450	609,000
	4,100	50	199	354	3.5 E+7	6.2 E+7	221,122	182,342
	2,000	30	218	387	5,527,053	9,073,33	52,281	45,467

(Continued)

[1] The flexural strength R of the concrete is assumed to be 650 psi.
[2] Assumed values.
[3] The subgrade reaction k is obtained from the relationship between k and subgrade modulus E in Figure 13.
[4] Computed layered elastic stress using BISAR program.
[5] Computed free edge stress using H-51 program.
[6] Coverage computed from the equation shown in Figure 8.
[7] Coverage computed from Equation 2 with $\sigma_e = \sigma_e \times 1.0$.
[8] Coverage computed from Equation 2 with $\sigma_e = \sigma_e \times 0.75$.
[9] Coverage computed from Equation 7.

Table 7 (Concluded)

Concrete Thickness in. (1)	Subgrade E psi (2)	k pci (3)	σ_{LE} psi (4)	σ_w psi (5)	Layered Elastic with Load, Transfer (6)	Predicted Westergaard with Load Transfer (7)	Coverages Westergaard no Load Transfer (8)	Proposed Layered Elastic, no Load Transfer (9)
10	10,000	100	136	225	6.4 E+11	2.6 E+13	3.6 E+9	2.9 E+8
	7,000	80	142	233	1.7 E+11	7.6 E+12	1.4 E+9	1.1 E+8
	4,100	50	151	255	3.0 E+10	3.9 E+11	1.6 E+8	1.9 E+7
	2,000	30	163	271	3.8 E+9	3.3 E+10	2.4 E+7	6.2 E+6

[1] The flexural strength R of the concrete is assumed to be 650 psi.
[2] Assumed values.
[3] The subgrade reaction k is obtained from the relationship between k and subgrade modulus E in Figure 13.
[4] Computed layered elastic stress using BISAR program.
[5] Computed free edge stress using H-51 program.
[6] Coverage computed from the equation shown in Figure 8.
[7] Coverage computed from Equation 2 with $\sigma_e = \sigma_e \times 1.0$.
[8] Coverage computed from Equation 2 with $\sigma_e = \sigma_e \times 0.75$.
[9] Coverage computed from Equation 7.

PART V: DISCREPANCY BETWEEN THE CONVENTIONAL PROCEDURE AND THE ELASTIC LAYERED METHOD

47. In the current design procedure, the magnitude and compositions of traffic are accounted for by the DI, together with the concept of equivalent 18,000-lb basic loading, and the thickness design is based on the computed free edge stress using the H-51 computer program. The DI is not used in the elastic layered method, and the thickness design is based on the computed interior stresses induced by traffic loads using the BISAR program. In general, thickness designed by the two procedures are very close except in certain conditions where the elastic layered method is more reasonable. These are explained as follows.

- a. When traffic is characterized by DI numbers, the concrete thickness may vary greatly when the traffic is changing from one index number to the other. This is not the case for elastic layered method since the traffic is directly input into the computations. This is particularly true when the index number is increased by more than one.
- b. The DI method has another drawback. When the pavement is designed for two different types of vehicles, the heavier vehicle is the governing one as it requires the highest DI. In this case the vehicles requiring lower DI are discarded in determining the pavement thickness. As in the design example shown in TM 5-822-6/AFM 88-7 (Headquarters, Department of the Army and Air Force 1986), the DI is 6 for the 50,000-lb tracked vehicles (50 per lane per day) and is 7 for the 80,000-lb tracked vehicles (20 per lane per day). Since the 80,000-lb tracked vehicle traffic is the governing factor as it requires the highest DI, the design is thus based on the DI of 7, and the effect of the 50,000-lb tracked vehicle traffic on the design is discarded. This is not the case in the elastic layered design procedure as each group of the traffic is input into the computation and the design is based on the sum of the effects of all the traffic, regardless of magnitudes.

PART VI: SUMMARY

48. The current design procedure of rigid pavements for roads, streets, walks, and open storage areas was reviewed. The development of the procedure using elastic layered method and the discrepancies between the two procedures were presented.

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